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Use of local convective and radiant cooling at warm environment: effect on thermal comfort and perceived air quality

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SUMMARY

The effect of four local cooling devices (convective, radiant and combined) on thermal comfort and perceived air quality reported by 24 subjects at 28 °C and 50% RH was studied. The devices studied were: (1) desk cooling fan, (2) personalized ventilation providing clean air, (3) two radiant panels and (4) two radiant panels with one panel equipped with small fans. A reference condition without cooling was tested as well. The response of the subjects to the exposed conditions was collected by computerized questionnaires. The cooling devices significantly ($p < 0.05$) improved subjects' thermal comfort compared to without cooling. The acceptability of the thermal environment was similar for all cooling devices. The acceptability of air movement and PAQ increased when the local cooling methods were used. The best results were achieved with personalized ventilation and cooling fan. The improvement in PAQ when the radiant panel was used alone was minimal.

KEYWORDS

Human response, warm environment, air movement control, personalised ventilation

1 INTRODUCTION

The strategy of keeping room air temperature high (2-3 °C above the comfortable room temperature) and improving occupants' thermal comfort by local convective cooling with air movement at elevated velocity is suggested in the present standards. The strategy may lead to energy saving in some buildings, however, in other buildings it may have the opposite effect, i.e. may lead to increase of the energy use (Schiavon and Melikov, 2008). It has been also documented that perceived air quality (PAQ) decreases and SBS (Sick Building Syndrome) symptoms increase when pollution, temperature and relative humidity of inhaled air increase (ASHRAE Guideline 10 2011). Air movement with increased velocity (especially when facially applied) improves PAQ (also thermal comfort) but it does not affect positively the SBS symptoms (Melikov and Kaczmarczyk 2012, Melikov et al. 2012). An increase in air temperature and relative humidity decreases the evaporation of the tear film and thus the blink rate, while increase of air velocity increases the evaporation and results in increase of the blink rate (Wolkoff et al. 2003). High indoor air pollution has negative impact on eye. Research indicates that facially applied flow of polluted room air didn't have significant impact on blink rate compared with the case without air movement and that the increase of blink rate due to decrease of temperature and humidity and increase of velocity may be compensated due to the increase in air cleanness (Melikov et al. 2011).

Local radiant cooling can also be used for improving occupants' thermal comfort at warm environment, especially local cooling of the head (which is an active heat dissipater) and the upper body part. In this case occupants' will breathe warm and polluted room air. The simultaneous impact of radiant cooling of the face and inhaling warm polluted room air on the PAQ is not known. It may be expected that the negative effect of warm air on PAQ will be compensated by the local radiant cooling. However this needs to be studied. The combined impact of radiant cooling and increase of room air temperature on eye discomfort has not been studied. Similarly as in the case of PAQ radiant cooling of the face may diminish the effect of warm and polluted air on tear film stability and affect eye blink rate.

Local cooling, convective or radiant, generates non-uniform thermal environment. The control of the local convective cooling is fast and therefore it can be used at workstation under the individual control of occupants. The control of radiant cooling (e.g. by cooling panels) is slow and may not be effective, in some cases even frustrating for occupants. The separate and combined impact of convective and radiant local cooling on occupants' thermal comfort, PAQ, health (SBS symptoms, eye symptoms, etc.) and performance has not been studied sufficiently and the mechanisms are not well known. Human subject experiments were performed to study this impact. This paper presents results on thermal comfort and PAQ.

2 METHOD

Experiments with 24 subjects (15 males and 9 females) were carried out in a climate chamber with accurately controlled and monitored air temperature and humidity. Mean radiant temperature was equal to the air temperature, radiant asymmetry was low and low vertical air temperature gradient ($<0.2\text{ }^{\circ}\text{C}$) and air velocity ($<0.06\text{ m/s}$) were ensured by upward "piston flow" ventilation. Ten workstations (WS) were arranged in the chamber (Figure 1): 2 workstations (1 and 2) with personalized ventilation (PV), 2 workstations (3 and 4) with personal cooling fan (FAN), 2 workstations (7 and 8) with radiant panel (RP) or with radiant panels with small fans (RP with fans) and 2 workstations (5 and 6) without devices (W – referred to in the following as "No device"). The half of experiments using workstations 7 and 8 were performed with RP and the rest with RP with fans. There were partitions between the workstations. The desks with PV, FAN and RP were placed considering not influencing the other workstations. The workstations consisted of a desk, adjustable office chair, laptop PC, pen, box with set of paper questionnaires and box for collecting the filled-in questionnaires. Old carpet and linoleum with surface area equal to the floor area of the chamber hanged in a box (PS) and hidden from the subjects were used to generate typical office pollution.

The PV systems was equipped with a circular air terminal device (ATD) attached to a movable arm allowing to change the distance between the user and the ATD as well as the direction of the personalized flow. The ATD is designed for minimal mixing of the supplied clean personalized air with the polluted room air (Bolashikov et al. 2003). A workstation with the PV is shown in Figure 1a. During the experiments the subjects could adjust the position of ATD, the direction and the flow rate of the supplied personalized air. They were recorded. The FANs (each 30 W) were attached to the two desks (Figure 1b). The subject at the desk could adjust the height and direction of the fan as well as the velocity of the generated flow. These were continuously recorded. Two RP (0.6 m x 0.7 m each) were placed at two desks: one above and one below the desk table. The top panels were inclined to provide cooling to the upper body parts of the person at the workplace (Figure 1c). The panels below the desk cooled users' lower body, i.e. thighs, lower legs and feet. The back of the panels were insulated. Chilled water supply to the panels kept their surface temperature at $17\text{ }^{\circ}\text{C}$ (the lowest level without condensation). Due to the long response time of the radiant panels,

individual control of the surface temperature was not possible. For the experiments of RP+Fans, three small fans (DC 12 V each) and adjustable plates were attached to the upper radiant panels (Figure 1 d). The fans transported the warm room air downward along the panels. The air was cooled and then redirected to the person by the plate. In this way convective and radiant cooling was provided to subject's upper body. The power supply to the fans, i.e. the generated flow rate, was kept constant (defined in pre-tests). Subjects could adjust the direction of air flow (Figure 1d). The plate position was monitored and recorded.

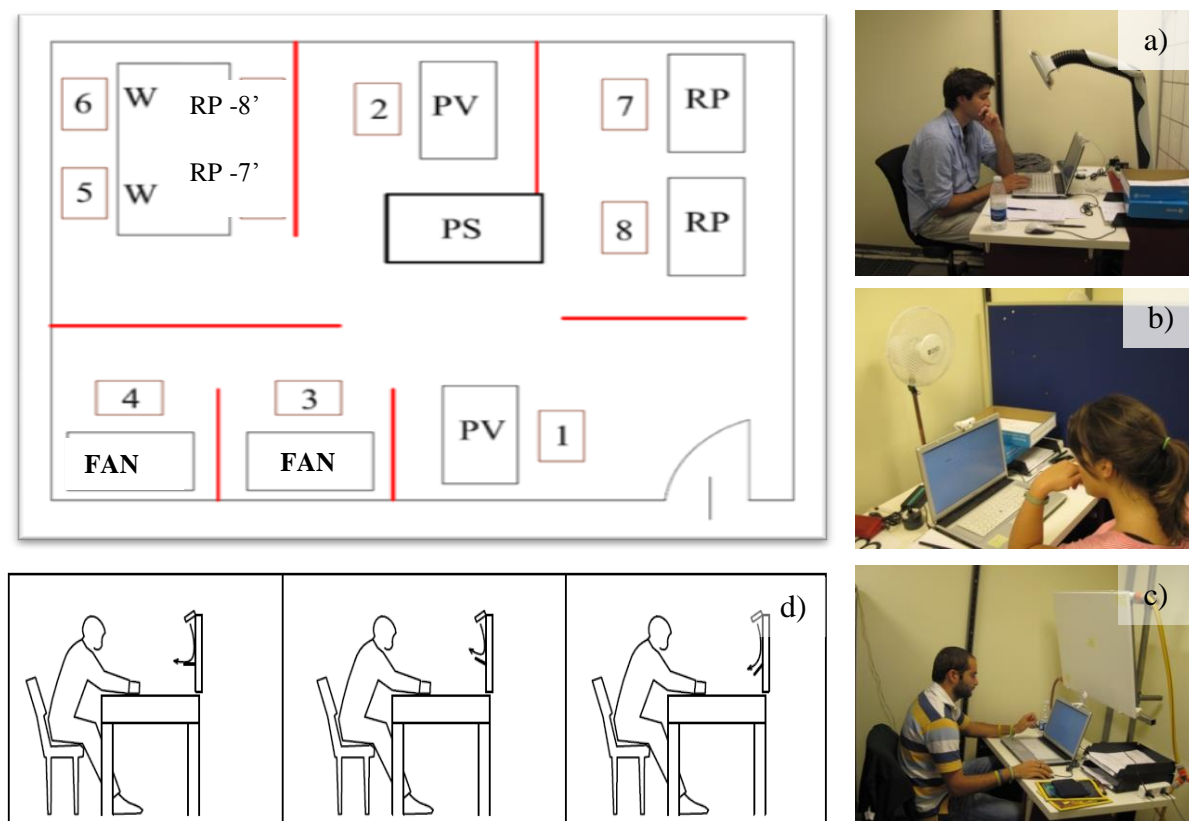


Figure 1. The layout in the chamber. Workstations with PV (a), PF(b) and RP (c), RP+Fans with plate to control flow direction (d) and No devices (W).

The subjects, all university students, were non smokers, did not have asthma, allergy and chronic diseases, did not wear glasses or contact lenses. During the experiments the subjects were asked to fill in several questionnaires. Most of the questionnaires were computerized but some were on paper. Subjects evaluated thermal sensation on ASHRAE's 7-point scale (cold: -3, cool: -2, slightly cool: -1, neutral: 0, slightly warm: 1, warm: 2, hot: 3), air movement and air movement preference (more, less or no change in air movement), odor intensity (no odor, slight odor, moderate odor, strong odor, very strong odor, overwhelming odor), air freshness on continuous scale (air stuffy – air fresh) and reported acceptability of thermal sensation and perceived air quality on continuous scale from clearly unacceptable (-1) to just unacceptable (-0.1) and then from just acceptable (0.1) to clearly acceptable (1). Furthermore questions on SBS symptoms and subjects' clothing were included (not reported). Subjects' performance was assessed by different tasks (not reported in this paper).

The subjects were divided in 3 groups of 8 people. Each group was assigned to participate in a specific weekday. The subjects were exposed randomly to four conditions: PV, FAN, RP (12 subjects) or RP with fans (12 subjects) and No device. The temperature in the chamber was

kept at 28 °C and relative humidity at 50%. Each experimental session started at 1 pm and lasted for 4 hours. The session was divided into three parts: first 30 min acclimatization to the conditions in the chamber without use of the devices, then 30 min acclimatization to the devices and 180 min performance tasks with use of the devices. There was 10 min break after 150 min, when the subjects could leave the chamber. The response on thermal comfort and air quality was collected at the beginning of the experiment, 15, 30, 35, 45, 55, 65, 110, 145, 205 and 240 min from the beginning of the experiment. During the experiment subjects could drink water. They were encouraged to modify their clothing to feel comfortable. Before the start of the experiment, the subjects spent about 10-15 min beside the chamber where the temperature was 20 °C. The workstations with PV (1 and 2), FAN (3 and 4) and No device (5 and 6) were used from the beginning of the experiment (it was easy to switch on the PV and the FAN after 30 min). Due to slow response of the radiant panels, their surface was kept constant during the whole experiment. The subjects assigned to use the workstations (7 and 8) with RP or with RP with fans spend the first 30 min of the experiment at workstations RP-7' and RP-8' (near the workstations 5 and 6). During the acclimatization periods subjects were allowed to read books or magazines. After that they were engaged with the performance tests.

3 RESULTS

For each subject, the results were analyzed to obtain average response for the period of exposure to the cooling devices as well as his/her response in time. Then the average response for all subjects was calculated. In the following only the average response of all subjects for the exposure period is discussed. The number of subjects exposed to the five conditions was: FAN and No device – 24 subjects, PV – 23 subjects, RP and RP+fans – 12 subjects. As was expected, the results showed that the use of the cooling methods improved subjects' thermal sensation for the whole body and for the body parts. Figure 2 shows the thermal sensation at the head and its acceptability. Thermal sensation acceptability was significantly ($p < 0.05$) higher when subjects used the PV and the FAN (and most of the time when they were exposed to the RP+Fans) than that recorded when subject was exposed to No device. The additional air movement generated at the RP with small fans (RP+fans) improved acceptability in comparison with RP alone. In general, the local cooling provided by the devices tended to improve local acceptability of the thermal sensation.

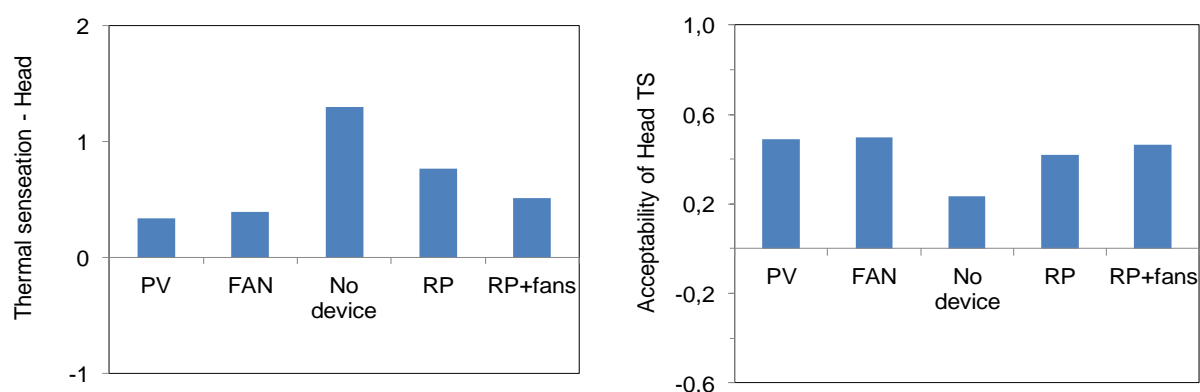


Figure 2. Thermal sensation for the head and its acceptability (average for all subjects).

The results on average perceived air quality were further analyzed and percent of dissatisfied was calculated as suggested by Gunnarsen and Fanger (1991). These results are shown in Figure 3. The results in the figure clearly indicate that more than 30% of the subjects were dissatisfied with the air quality when they did not use local cooling. The use of any of the local cooling methods decreased the percent of dissatisfied subjects. As shown in Figure 3, PV and FAN had the greatest impact. The additional air movement generated in the case

RP+Fans also helped to reduce substantially the percent of dissatisfied. In comparison with the case “No device”, the acceptability of PAQ increased significantly ($p<0.05$) when the PV and the FAN were used; the difference between the PV and the FAN was not significant. During most of the exposure period, RP+Fans improved significantly ($p<0.05$) the PAQ acceptability; the positive impact of RP on acceptability of PAQ was reported not so often in the exposure. The results for the air freshness were similar to that of the PAQ. As is compared in Figure 3, the air was felt most fresh when subjects cooled their body with the PV, followed by the FAN, RP+Fans and RP. Air was felt least fresh when subjects were exposed to No device. In comparison with the case “No device”, air freshness was significantly ($p<0.05$) higher when PV, FAN and RP+fans were used and only for some subjects when the RP were used. The air was felt significantly ($p<0.05$) more fresh with the PV compared with the FAN, the RP+fans and RP but not during the entire exposure. The use of the FAN improved the air freshness perception significantly ($p<0.05$) in comparison with the RP but not in comparison with the RP+fans.

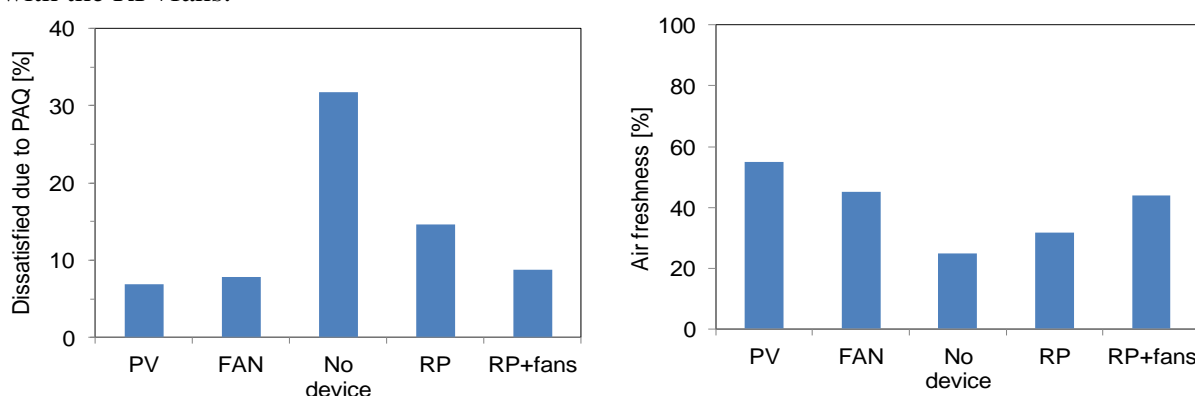


Figure 3. Dissatisfied subjects with PAQ and air freshness with the local cooling methods.

The air movement acceptability was improved by all local cooling devices compared with the “No device” case. The improvement was significant ($p<0.05$) except in the case with RP. The improvement provided by the PV and FAN was significantly higher than that from the RP+fans, but was not significantly different between the exposures to the PV and the FAN. In the case “No device” all subjects preferred more air movement from the beginning till the end of the experiment. Only few times during the exposure, 1-3 subjects did not request more air movement. The number of subjects with preference of more air movement decreased when RP+fans were used. Only few subjects reported on insufficient air movement when they used the PV and the FAN. However the analyses showed that they did not use the full capacity of the devices. The percent of dissatisfied subjects with the air movement is shown in Figure 4.

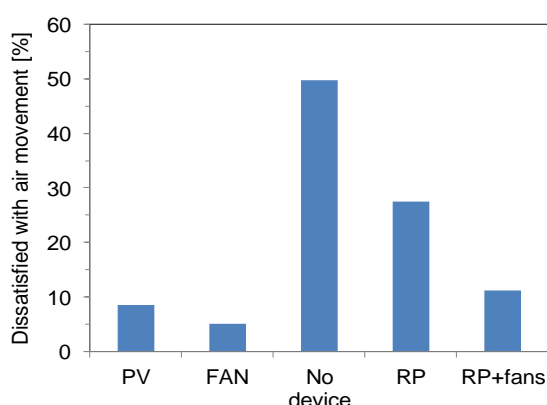


Figure 4. Dissatisfaction with air movement

4 DISCUSSION

As was expected, all local cooling methods improved subjects' thermal comfort compared with "No device" case. As was also expected, the elevated air movement improved the PAQ. The acceptability of PAQ reported by the subjects for the PV and the FAN cases was not different although the PV provided clean air and the Fan moved the polluted room air. However the clean PV air was felt fresher compared to the airflow from the FAN. The use of small fans with the RP, which generated weak flow, was able to significantly improve PAQ and air freshness and to decrease the dissatisfaction with air movement.

The combined impact of radiant cooling and warm inhaled air on PAQ was one of the effects to be studied. In the case of RP, the subjects inhaled warm polluted room air while their face was cooled. The acceptability of PAQ and air freshness improved (not significantly). The results suggest that local cooling of the face at warm environment will improve PAQ acceptability but not as much as air movement with elevated velocity. Melikov et al. (2012) reported on decreased headache when local radiant cooling of the head was used by subjects.

5 CONCLUSIONS

Local convective, radiant and combined cooling of the head region at warm environment improves subjects' thermal comfort and PAQ. The impact of convective cooling of the face on the PAQ was greater than the impact of the local radiant cooling. Additional air movement to local radiant cooling of the head region will improve greatly the PAQ. Further studies with large number of people are recommended to reveal the mechanisms of the impact of convective and radiant cooling on people's comfort, health and performance.

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